A PLAN FOR SEISMIC LOCATION CALIBRATION OF 30 IMS STATIONS IN EASTERN ASIA

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ABSTRACT

In March 2000, a collaborative academic-industry research consortium comprised of five institutions started an integrated series of projects, all with the goal of improving the capability to locate seismic events based on data acquired by International Monitoring System (IMS) stations in Eastern Asia. The focus of this effort is to develop and deliver validated high-resolution travel time grids for operational use in support of the location estimates made by the International Data Centre (IDC) of the Comprehensive Test Ban Treaty Organization. These are to be used for for the specified stations to locate on the order of a hundred events per day around the world. The basic approach is to use thousands of so-called "ground truth" seismic events in Eastern Asia that have been accurately located by regional or local networks. These will be used to obtain the travel times of key seismic phases from any point in the region to any of the 30 IMS stations that are the focus of the project. These travel-times will in general be a function of distance and azimuth --- and depth. They must be determined as a continuous function of postion, from the empirical discrete ground truth data; and they must be demonstrated to improve location estimates of new events, over the estimates obtained on the basis of current procedures (typically, based on the Earth model IASP91).

In the first project, the Lamont-Doherty Earth Observatory of Columbia University will contribute numerous newly-obtained ground truth locations in Eastern Asia whose errors are thought to be of the order of five km or better (so-called GT5 events) and that are expected to be large enough for detection at IMS stations. In most cases these events are recent enough for inclusion in the Reviewed Event Bulletin of the PIDC (since 1995). In the second project, the University of Wyoming will contribute observed travel times for about 3000 three-component recordings at stations widely deployed in the Soviet era to detect regional waves from 21 nuclear explosions carried out during the Deep Seismic Sounding program. This dataset is an invaluable resource for thorough calibration of major aseismic regions in Russia and Central Asia. We expect to be able to find analog seismograms for several of these 21 nuclear explosions, as recorded at Eastern Asia stations now identified as part of the IMS, or at stations that were operated at sites close to the IMS station locations. Our consortium personnel at the University of Wyoming are Scott Smithson, Elena Morozova, and Igor Morozov.

In the third project, Mission Research Corporation will derive and test travel time surfaces, for IMS stations, that fit the GT data and Calibration Event Bulletin data. The lead person at MRC for the consortium is Mark Fisk. URS Greiner Woodward Clyde will contribute some ground truth data for India, Nepal, Pakistan, and much 1D and 2D modeling experience; the University of Connecticut will contribute 3D modeling experience. Both these organizations, and Wyoming and Lamont, will work together in Project 4 to provide expected travel times to 30 IMS station locations in Eastern Asia. In this fourth project, detailed studies of a small percentage of our claimed GT5 events will be carried out for purposes of validation of their location quality. The consortium lead person at URS Greiner is Chandan Saikia, and at the University of Connecticut is Vernon Cormier. Mission Research Corporation will package all of the products of the consortium for delivery to the Center for Monitoring Research in the fifth project, including quantitative evaluation of location improvements. In the sixth project, an Experts Group Review process will provide overall guidance. In this work, a group of consultants will meet with consortium members at Lamont for a few days each year. They will give advice on GT events and on how to use phase picks of GT events to provide improved location estimates for events recorded regionally at IMS stations in East Asia.

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OBJECTIVE

This project is intended to assist the International Data Centre to improve the accuracy of estimates of the location of seismic events — and to reduce the uncertainty of such estimates — on the basis of an interpretation of the arrival times of standard seismic waves observed at 30 stations of the International Monitoring System located in Eastern Asia. Such improvement is needed, to meet the goals of the IDC in supplying the location estimates that could be the basis of an on-site inspection request.

To see what accuracy is needed, we may quote the CTBT Protocol, Part II, ¶3:

"The area of an on-site inspection shall be continuous and its size shall not exceed 1000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction."

Also, ¶41(b) states (with reference to an OSI request) that the proposed boundaries of the area to be inspected are to be specified on a map in accordance with ¶3.

RESEARCH ACCOMPLISHED

At this time of writing our project has been running for about 4 of an anticipated 36 months. So far, we have identified and obtained a number of relevant ground truth datasets in Eastern Asia; and we have begun the work of obtaining accurate travel times (for different phases, as a function of distance, azimuth, depth) for six stations in Central Asia.

In subsections that follow, we give a general rationale for this type of work (improvements in global bulletins of seismicity); a summary of the main method we are using; an overall timetable for the project; and some specifics concerning the first group of stations for which we expect to report results.

RATIONALE

Major users of seismic data include:

- the national and international groups now being organized to monitor compliance with the Comprehensive Nuclear Test-Ban Treaty
- researchers who improve our knowledge of Earth's internal structure and the physics of earthquake processes; and
- those engaged in earthquake engineering and earthquake hazard mitigation.

Although the most basic data in seismology for all these users are seismograms, in practice the great majority of those who work with seismic data do not use seismograms directly. Instead they mostly use data products derived from seismograms. The most important of these products, are bulletins of seismicity.

In the last 20 years there have been enormous improvements in the quality and quantity of seismograms, associated with the development of broadband feedback sensors and techniques of digital recording to permit high dynamic range across wide bands of frequency. There is ongoing revolutionary improvement in access to seismogram data, as satellite communications and the Internet spread even to remote locations. It has therefore been frustrating to find that the quality of the principal data product derived from seismograms acquired internationally, the global bulletin of seismicity, has not yet seen the types of radical improvement needed by any of the user communities, listed above.

The US Geological Survey (USGS) and the International Seismological Centre (ISC) publish their bulletins months to years in arrears, using volunteered data, and methods of analysis that essentially have not changed for sixty years. These are very useful bulletins, and their quality has greatly improved because of the increased number of reported signal detections. The Reviewed Event Bulletin (REB) of the CTBT monitoring community, produced since 1995 January 01 by GSETT-3 and the PIDC and now by the IDC in Vienna, is vastly improved over the other global bulletins in its timeliness of publication. However, both the REB location estimates, and the estimates of their uncertainty (error ellipses), require improvement.

It appears that the principal reason for inaccuracies in the REB locations is lack of a sufficiently good model of Earth structure, and specifically of travel time information. It is desirable to calibrate each IMS station so that in effect the location of a new event can be located with reference to another event, whose location is known accurately and which, preferably, is not far from the new event. By using a sufficiently large number of calibration events, whose location is accurately known and whose signals are detected reliably at IMS stations, it is possible to generate a station-based travel time surface (a function of distance and azimuth), for each seismic phase. Different surfaces are needed for different event depths. For CTBT monitoring, the most important surface is that for zero depth.

As noted in the report of the first Oslo Workshop on IMS Location Calibration (January 1999, which led to the paper CTBT/WGB/TL - 2/18):
"such calibration is necessary in order to significantly improve the location precision of internationally reporting earthquake agencies,"
and
"no attempt has so far been made to include such corrections in routine location processing on a global scale."
Our consortium project will carry out such an approach to calibration for 30 IMS stations.

SUMMARY OF METHOD

The IMS stations in East Asia which are the subject of this project, are listed in Table 1, and shown in Figure 1, with station coordinates as originally given in Annex 1 to the CTBT Protocol. Not all of these sites currently have operational IMS stations. However, in some cases there are non-IMS stations which are operating at or near the IMS site, and in other cases stations have operated near the IMS site in the past. In general we refer to such non-IMS stations as surrogate stations. Their data may be used to assist in building up the necessary station-based travel-time data set for purposes of obtaining the types of travel-time surface needed at the IDC for every IMS station site.

Code	**Country**	**Station Name**	**Lat**	**Long**
PS12	China	Hailar	49.27	119.74
PS13	China	Lanzhou	36.09	103.84
PS23	Kazakhstan	Makanchi	46.80	82.00
PS25	Mongolia	Javhlant	47.99	106.77
PS29	Pakistan	Pari	33.65	73.25
PS31	Republic of Korea	Wonju	37.50	127.90
PS33	Russian Federation	Zalesovo	53.94	84.81
PS34	Russian Federation	Norilsk	69.40	88.10
PS35	Russian Federation	Peleduy	59.63	112.70
PS37	Russian Federation	Ussuriysk	44.28	132.08
PS41	Thailand	Chiang Mai	18.80	99.00
AS7	Bangladesh	Chittagong	22.40	91.80
AS20	China	Baijiatuan	40.02	116.17
AS21	China	Kunming	25.15	102.75
AS22	China	Sheshan	31.10	121.19
AS23	China	Xi'an	34.04	108.92
AS57	Kazakhstan	Borovoye	53.06	70.28
AS58	Kazakhstan	Kurchatov	50.72	78.62
AS59	Kazakhstan	Aktyubinsk	50.40	58.00
AS60	Kyrgyzstan	Ala-Archa	42.64	74.49
AS68	Nepal	Everest	27.96	86.82
AS86	Russian Federation	Seymchan	62.93	152.37
AS87	Russian Federation	Talaya	51.68	103.64
AS88	Russian Federation	Yakutsk	62.01	129.43
AS89	Russian Federation	Urgal	51.10	132.36
AS90	Russian Federation	Bilibino	68.04	166.37
AS91	Russian Federation	Tiksi	71.66	128.87
AS92	Russian Federation	Yuzhno-Sakhalinsk	46.95	142.75
AS93	Russian Federation	Magadan	59.58	150.78
AS100	Sri Lanka	Colombo	6.90	79.90

Table 1. IMS stations in Eastern Asia. A TBD Primary station (PS20) and a TBD Auxiliary station (AS39) may eventually be negotiated in Eastern Asia.

Table 2 lists our present knowledge of the availability of data at each of the 30 IMS sites in Table 1, whether or not there is an IMS station currently operating at the site. In the case where no IMS station is operating, we list some appropriate surrogate stations. Our basic approach will be to acquire lists of reliably located seismic events in Eastern Asia, preferably occurring since the beginning of publication of the REB on January 1, 1995 and large enough to be included in the REB. From such events, preferably of GT5 quality or better, we shall obtain the picked arrival times at IMS stations and thus build up a set of station-based travel-times for events of accurately known location.

For each major set of event locations that we plan to use for IMS station calibration, an extensive validation effort will be made. We plan to do this by acquiring waveform data and phase-pick data for a subset of the events, from as many stations as possible. From such data we shall make our own location estimates, including waveform studies of the depth, in order to validate our conclusions as to the quality of the locations. For the major aseismic areas of Eastern Asia (for example, for much of the northern part of this region, which is in Russia), such an approach cannot be used. However, we are fortunate in that major reflection/refraction profiles were carried out in this region during the Soviet era, in the Deep Seismic Sounding program (DSS). Extensive DSS data will be analyzed in our consortium project by the University of Wyoming. Specifically, arrival times will be picked, and interpreted to generate 2D and 3D regional models and hence travel-times to IMS station sites in Russia.

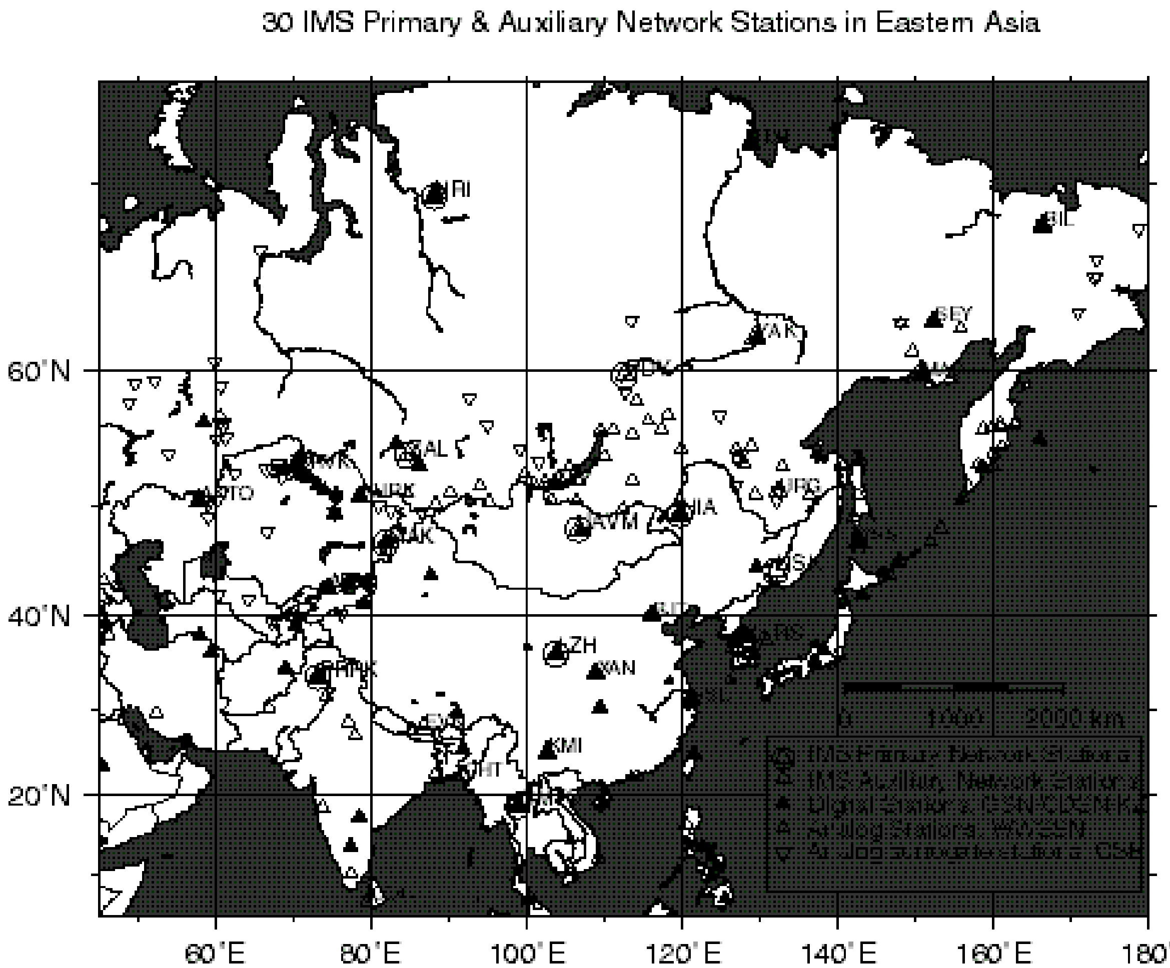

Figure 1. IMS primary and auxiliary stations in our project, and surrogate station locations.

Code IMS	ISC	PIDC	Phase data Operator	Digital waveform data Operation	Source	Analog waveform data
HIA		HIA	CDSN	1986/07-	DMC/IDC	
LZH	LZH		CDSN	1986/06-	DMC	
MAK			KZ/GSN	1994/07-	LDEO	
JAVM	ULN	ULN	GSN (ULN)	1994/11-	DMC	
PRPK	NIL	NIL	GSN (NIL)	1994/12-	DMC	
KSRS		KSAR	KIGAM	1995/01-	IDC/KIGAM	
ZAL	NVS, ELT		ZAL IDC (ZAL)	1995/01	IDC+ELT (1998/08-, LDEO)	
NRI	NRI	NRI	GSN (NRIL)	1992/12-	DMC/IDC	1964-, Obninsk
PDY	BOD	PDY	IDC	1995/01-	IDC	
USK	VLA		CDSN (MDJ)	1986/10-	DMC	
CMTO	CHG,CHTO		GSN (CHTO)	1992/09-	DMC	
CHT	SHL,HOW		GSN (SHIO)		DMC	HOW, SHL/WWSSN (LDEO)
BJT	PEK,BJI	BJT	CDSN (BJI)	1986/07-	DMC	
KMI	KMI		CDSN (KMI)	1986/06-	DMC	
SSE	SSE		CDSN (SSE)	1986/06-	DMC	
XAN	XAN		CDSN (XAN)	1992/11-	DMC	
BRVK			KZ/GSN	1994/07-	LDEO	
KURK			KZ/GSN	1994/07-	LDEO	
AKTO			KZ	1994/09-	LDEO	
AAK	FRU		GSN (AAK)	1990/10-	DMC	
EVN	DMN,KKN			1991/06-11	ING	
SEY	SEY		GS/GSRAS	1990/09-	DMC/GS	1969- Magadan
TLY	IRK		GSN/GSRAS	1990/10-	DMC	1964- Irkutsk
YAK	YAK	YAK	GSN/GSRAS	1993/08-	DMC	
URG					Sogda 75/01-76/10 CSE	
BIL	ILT		GSN/GSRAS	1995/08-	DMC	Bilibino 64- Magadan
TIXI	TIK		GSN/GSRAS	1995/08-	DMC	1964- Obninsk
YSS	YSS		GSN/GSRAS	1992/05-	DMC	
MA2	MAG,MGD		GSN/GSRAS	1993/09-	DMC	1964- Magadan
COC	KOD		AWRE (GBA)			KOD 1964-'90 WWSSN LDEO

Table 2. A summary of information on data (picks, waveforms) at 30 IMS sites, listing the operating IMS stations, and surrogate stations, useful for acquiring phase picks and waveforms for stations in Table 1.

Station operators are:
GSN = Global Seismographic Network;
CDSN = Chinese Digital Seismographic Network;
KZ = Kazakhstan Broadband Seismographic Network (NNC, RK/LDEO);
GS = GeoScope;
GSRAS = Geophysical Survey, Russian Academy of Sciences
Data sources are:
IDC = International Data Centre for IMS;
DMC = IRIS Data Management Center
ING = The National Institute of Geophysics, Italy

The AWRE operation of GBA has ended, with this station handed over to local operation, but much relevant data for this station is easily available.

We note that a sophisticated modeling effort is the only way to set up the required travel time grid for each IMS station, in two important cases: from large aseismic regions; and to IMS station locations where no station or nearby surrogate now exists. But we are well aware that it would be inappropriate for the IDC to rely for its monitoring operations on purely 3D calculations in a 3D model. Therefore we shall make great efforts to search for appropriate validation, to the extent possible, of any predicted effects on travel times caused by 3D structure. It is here that a search for data from old analog stations can play a key role. We are familiar with analog stations all over the former Soviet Union which operated during the period 1965 — 1990 at locations that were selected in 1996 to become the sites of modern instrumentation (IMS); and we plan to track down old data from these stations (see Table 2), and to

work with scientists in Russia and Central Asia to analyze them. This work will bring together old analog data at fixed stations, the special DSS field data, modern waveform data, and the full sophistication of modeling in 1D, 2D, and 3D structures.

OVERALL TIMETABLE

The thirty IMS stations we are studying in Eastern Asia can be grouped geographically into five regions, and the consortium expects to propose to the Configuration Control Board of the Center for Monitoring Studies, on travel-time grids for IMS sites, in the following sequence of regions:

Central Asia (MAK, BRVK, KURK, AAK, AKTO, ZAL) ~ year two, first quarter
China (HIA, LZH, JAVM, BJT, KMI, SSE, XAN) ~ year two, fourth quarter
Korea (KSRS) ~ year three, second quarter
Russia (NRI, PDY, USK, SEY, TLY, YAK, URG, BIL, TIXI, YSS, MAG) ~ year three, fourth quarter
Indian subcontinent (PRPK, CHT, EVN, COC) and CMTO ~ year three, fourth quarter

SOME SPECIFICS CONCERNING THE FIRST GROUP OF STATIONS

As noted above, the first set of stations for which we plan to deliver the necessary station-specific travel time information is MAK, BRVK, KURK, AAK, AKTO, ZAL. These Central Asian stations are indicated in Figure 2. It may be possible to include additional stations, such as NIL (surrogate for PRPK — noting that NIL has been picked by the PIDC in recent years), and possibly some stations in China. It would appear that the work of documenting improvements in event location can be done better if the travel-time information is supplied for a larger number of stations. In the case of Central Asia stations, such travel times will be obtained in our project on the basis of (a) early studies based mainly on earthquake data (e.g. the work of Nersesov and Rautian, using stations of the Complex Seismological Expedition), (b) Deep Seismic Sounding, and (c) recent studies of nuclear and chemical explosions. We are also using (d) an empirical approach in which phases are picked at IMS stations, for so-called Ground Truth events whose location is known quite accurately on the basis of additional data, obtained for example from local and regional networks.

Of the IMS stations in and near Kazakhstan that we are now studying, only ZAL has been contributing data to the PIDC or IDC. Thus phases at ZAL, and only at ZAL, have been picked for numerous events in our GT datasets in recent years. Under a joint program between the National Nuclear Centre of the Republic of Kazakhstan and the Lamont-Doherty Earth Observatory of Columbia University in New York, Kazakhstan stations AKTO, BRVK, KURK and MAK have operated with high quality sensors and digital recording throughout the period of full-time production of the REB. Station AAK has also operated throughout this period (i.e., since 1995 January 1), and continuous data from all these stations are easily available. Since these stations have not yet contributed data to the PIDC/IDC as yet, it will be necessary to obtain picks at these stations for many events in our GT datasets.

With these picks, we shall first have to go through a process of re-creating REB locations with the Central Asia station picks included, using the same travel times (*iasp91*) that have been used for this region by the PIDC. Second, we shall go through an iterative process of (a) developing stations-specific travel-times, (b) re-locating events, and (c) documenting improvements in the resulting event locations (as compared to those in the re-created REB). It is only on the basis of demonstrated improvements in event locations, that stations-specific travel-times will be acceptable and used for improved event location in future.

Because of the excellent signal-to-noise ratio of Kazakhstan stations, in particular of BRVK, KURK, MAK, it is likely that they will detect signals for a large fraction of global seismicity reported by the IDC. The impact that Kazakhstan IMS stations will have on the REB (when these stations are eventually included in the IMS) will be significantly greater if station-specific travel-times are available for them *ab initio*.

CONCLUSIONS AND RECOMMENDATIONS

It appears that the Reviewed Event Bulletin of the International Data Centre will be the first bulletin of global seismicity to be published using stations for which arrival times are interpreted with station-specific travel time information. Such an approach is potentially a major improvement upon current practice. Our work is to provide such station-specific information for thirty stations of the International Monitoring System in Eastern Asia.

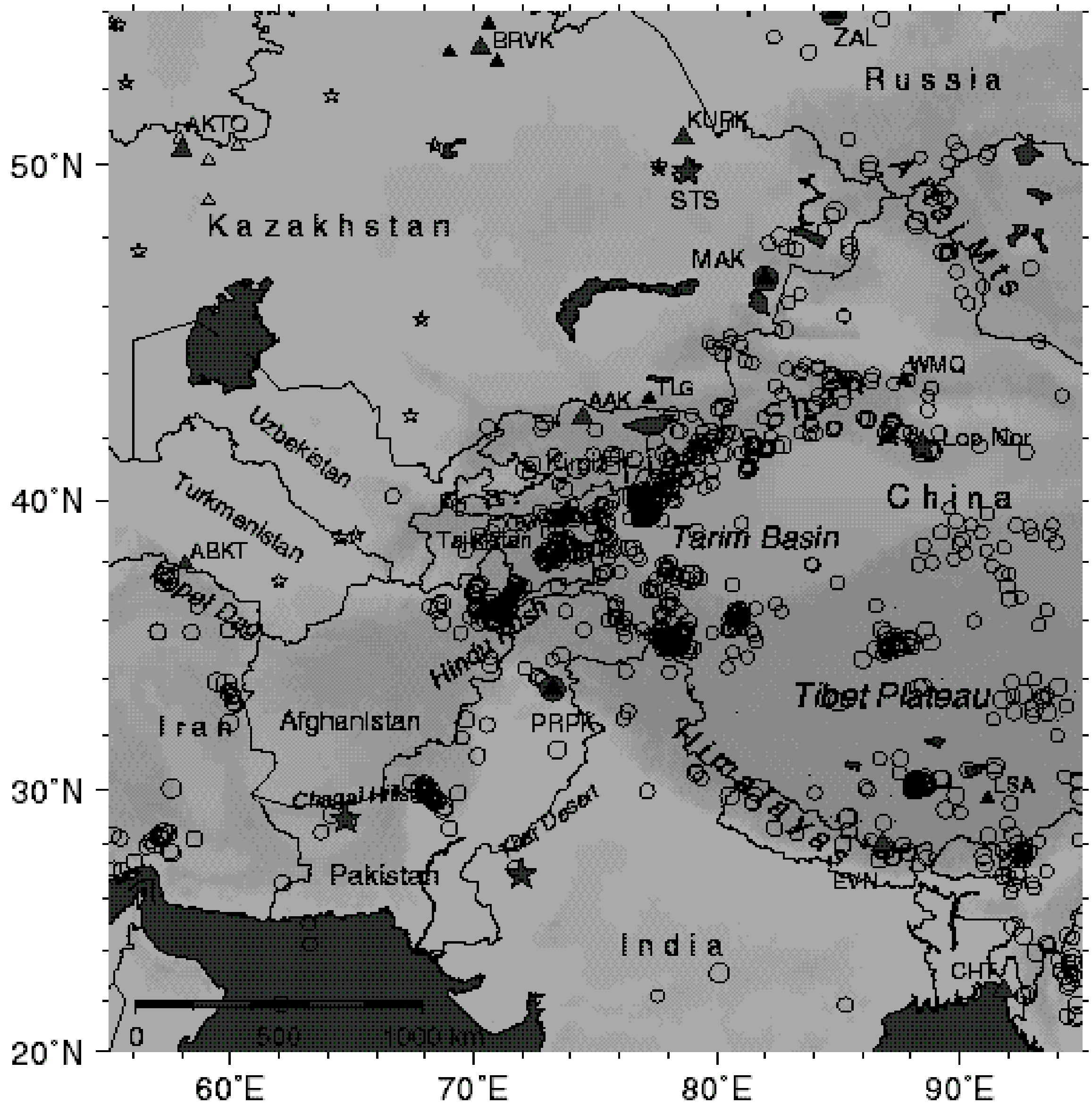

Figure 2. Central Asia map showing locations of IMS primary stations (circle with black triangle), auxiliary stations (white triangle), other digital stations (black triangle), analog stations (open triangle), underground nuclear explosion test sites (big star), and PNEs (small star). Circles are used to indicate GT events.

We do not know as yet whether the desired degree of improvement in location accuracy (for seismic events published in the REB) can be achieved on the basis of phase picks and station-specific travel times. This question should be examined on an annual basis for the next few years. Recognizing that eventually it may be appropriate to use methods based on whole waveforms (such methods have been demonstrated to lead to remarkably accurate event locations in regional bulletins that document dense seismicity, for example in parts of California), we recommend that research also be carried out using waveform-based methods in the context of global bulletin publication (at least, for areas which are seismically most active).

Key Words CTBT, earthquake location, seismicity bulletins